

Thermodynamic analysis of PID temperature controlled heat pump system[☆]

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ABSTRACT

In the current research, a heat pump fluidized bed dryer with PID temperature control was designed. Drying air temperature was determined as 40 °C and it was controlled through this system with ± 0.36 °C uncertainty. The designed and manufactured PID controlled heat pump dryer was analyzed by drying the plants of mint, parsley and basil. These analyses included the energy analysis, energy utilization ratio, exergy analysis and uncertainty analysis. In this system, drying air velocity was changed depending on the set temperature. As the set temperature increased, drying air velocity decreased as well. Drying air velocity varied from min 1.01 to max 7.4 m/s. Therefore, energy utilization ratio (EUR) in the fluidized bed dryer was changed during the drying period between 16% and 90%. The whole system heating coefficient of performance (COP_{ws}) was calculated as an average of 1.91.

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1. Introduction

Drying is one of the oldest and most prevalent industrial methods. It is widely used in the chemical, agricultural, pulp and paper, mineral processing and wood processing industries [1]. In the industrial applications, the control of the drying air temperature is the most important parameter. For that reason, controlling the heat pump systems for drying air temperature are very suitable [2].

A great many studies have been carried out for the heat pump drying systems in the literature. Ceylan and Aktaş [3] designed and manufactured a PID controlled heat pump dryer. The heat pump dryer was tested by drying hazelnuts and energy analyses were made. Shi et al. [4] investigated heat pump drying kinetics and quality characteristics of yacon at different drying temperatures and air velocities. Fatouh et al. [5] designed a heat pump assisting dryer and constructed it to investigate the drying characteristics of various herbs experimentally. Şevik et al. [6] proposed a simple and cost effective solar assisted heat pump system (SAHP) with flat plate collectors and a water source heat pump.

Over 400 types of dryers have been reported up to now, whereas more than 100 distinct types are commonly available. In this study, we designed a heat pump fluidized bed dryer to use in industrial applications. The PID controlled heat pump fluidized bed dryer was designed and experimentally analyzed to dry mint, parsley and basil.

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Nomenclature			
C_p	specific heat, kJ/kgK	\dot{m}_d	drying amount, g/h
\bar{C}_p	average specific heat, kJ/kgK	e	exergy, kJ/kg
\dot{m}	mass flow rate, kg/s	S	specific entropy, kJ/kgK
Q_{cd}	heat delivered in the condenser, kJ/s	V	volumetric flow rate of air, m ³ /s
Q_{fd}	heat used during moisture extraction in fluidized bed dryer, kJ/s	MC	moisture content, g water / g dry matter
T	temperature, K	M_i	initial wet weight, g
HPD	heat pump dryer	M_d	final dry weight, g
W	energy utilization, kJ/s		
ω	specific humidity, g/g	Subscript	
V	velocity, m/s	wi	water inlet
ρ	density, kg/m ³	we	water evaporation
W_{c2}	power input to compressor, kW	wo	water outlet
$W_{f7,8}$	power input the fans, kW	i	inlet
h	enthalpy, kJ/kg	oa	outlet air
COP_{ws}	heating coefficient of performance for whole system	ws	whole system
$SMER_{ws}$	specific moisture extraction rate for whole system	fbd	fluidized bed dryer
		ia	inlet air
		mp	moisture product

2. Experimental setup

An ordinary fluidized bed drying system consists of a blower, a heater, a dehumidifier (optional), a fluidized bed chamber, and a cyclone, whereas an ordinary heat pump drying system consists of an evaporator, a compressor, a condenser, and an expansion valve. By combining fluidized bed and heat pump drying systems, where the evaporator acts as a dehumidifier and the condenser is used as a heater, a heat pump fluidized bed dryer is formed [1].

The advantages offered by a heat pump fluidized bed dryer are as follows: low energy consumption due to high specific moisture extraction rate (SMER), high coefficient of performance (COP), wide range of drying temperature (−20 to 110 °C), environmental friendliness and high product quality. Thus, this type of dryer is suitable for heat-sensitive products such as food and products of bio-origin [1].

The PID controlled heat pump fluidized bed dryer is shown in Fig. 1. The system was consisted of a compressor, a condenser, an evaporator, an expansion valve, a fluidized bed, an evaporator and a condenser fan. Measurement and control devices and their characteristics are shown in Table 1. In the system, an inverter and a process control equipment was used to control the drying air temperature. In the heat pump drying process, the process control equipment was set to 40 °C. The drying air temperature was controlled by adjusting fan velocity according to set temperature. Fan velocity was increased or decreased by the inverter versus the set temperature. During the drying process, drying air temperature was controlled as 40 °C. The flow diagram of temperature control is shown in Fig. 2.

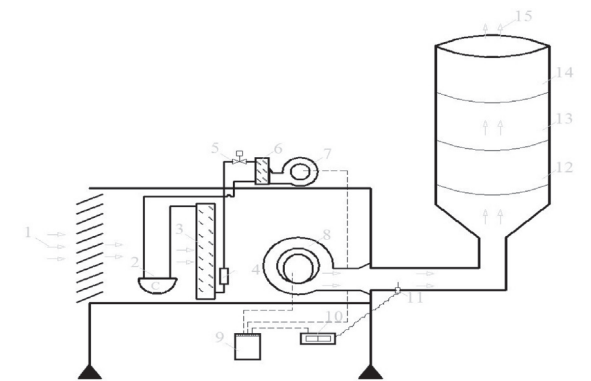


Fig. 1. Schematic view of PID controlled heat pump fluidized bed dryer. 1. Fresh air inlet (damper), 2. Compressor, 3. Condenser, 4. Filter, 5. Thermostatic expansion valve, 6. Evaporator, 7–8. Fan, 9. Inverter, 10. Process control equipment, 11. Thermocouple, 12. Drying shelf of basil, 13. Drying shelf of mint, 14. Drying shelf of parsley, 15. Exhaust air.

Table 1
Measurement and control devices and their characteristics.

Equipments		Properties
Thermohygrometer	TESTO	Temperature -200, +1370 °C Accuracy $\pm 2.5\%RH$ (+5 ... +95%RH) K type sensor
Inverter	ABB	AC variable speed drive mono phase induction motors 0.75 kW (1 HP)
Anemometer	DELTA OHM	Vane probe, $\varnothing 1 \times 6$ mm, speed from 0.8 m/s to 20 m/s.
Process control equipment	ORDEL	PC440, 4 kW, 100–240 VAC, transmitter supplement 24 VDC, auto-tuning, PID control
Digital balance 6.1 kg	METLER TOLEDO	Accuracy 0.01 g

3. Experimental procedure

Before the experiments of drying mint, parsley and basil, following preparations were made.

- Stems of mint, parsley and basil were extracted from leaves.
- Crops were washed, and then the water on the crops were evaporated in ambient air temperature.
- Before the drying process, the initial moisture content of the mint, parsley and basil was determined by drying them in a kiln which had been preheated to 105 ± 1 °C. At the end of two consecutive measurements, where the weight was less than 1%, the products were then accepted as exactly dry.
- Three different crops (parsley, mint, basil) were placed on the shelf then the drying process started.

The moisture contents and moisture ratios were calculated using the following equations [7].

$$MC_{db} = \frac{M_i - M_d}{M_d} \quad (1)$$

$$MC_{wb} = \frac{M_i - M_d}{M_w} \quad (2)$$

$$MR = \frac{M - M_e}{M_o - M_e} \quad (3)$$

$$DR = \frac{M_{t+dt} - M_t}{dt} \quad (4)$$

4. Energy analysis

General equation of mass conservation of drying air [3]:

$$\sum \dot{m}_i = \sum \dot{m}_o \quad (5)$$

General equation of mass conservation of drying moisture:

$$\sum (\dot{m}_{wi} + \dot{m}_{mp}) = \sum \dot{m}_{wo} \quad (6)$$

or

$$\sum (\dot{m}_{wi} \cdot \omega_i + \dot{m}_{mp}) = \sum \dot{m}_{oa} \cdot \omega_o \quad (7)$$

General equation of energy conservation:

$$\dot{Q}_{cd} - \dot{W} = \sum \dot{m}_{ia} \cdot \left(h_{oa} - h_{ia} + \frac{V_o^2 - V_i^2}{2} \right) \quad (8)$$

Heat used during moisture extraction in fluidized bed dryer of following equation:

$$\dot{Q}_{fbd} = \dot{m}_{ia} (h_{ia} - h_{oa}) \quad (9)$$

The heat delivered in the condenser \dot{Q}_{cd} was estimated using the experimental values of the following items as:

$$\dot{Q}_{cd} = \dot{m}_{ia} \cdot C_{p,air} \cdot (T_{ia} - T_{fdi}) \quad (10)$$

$$\dot{m}_{ia} = \rho_{ia} \cdot \dot{V}_i \quad (11)$$

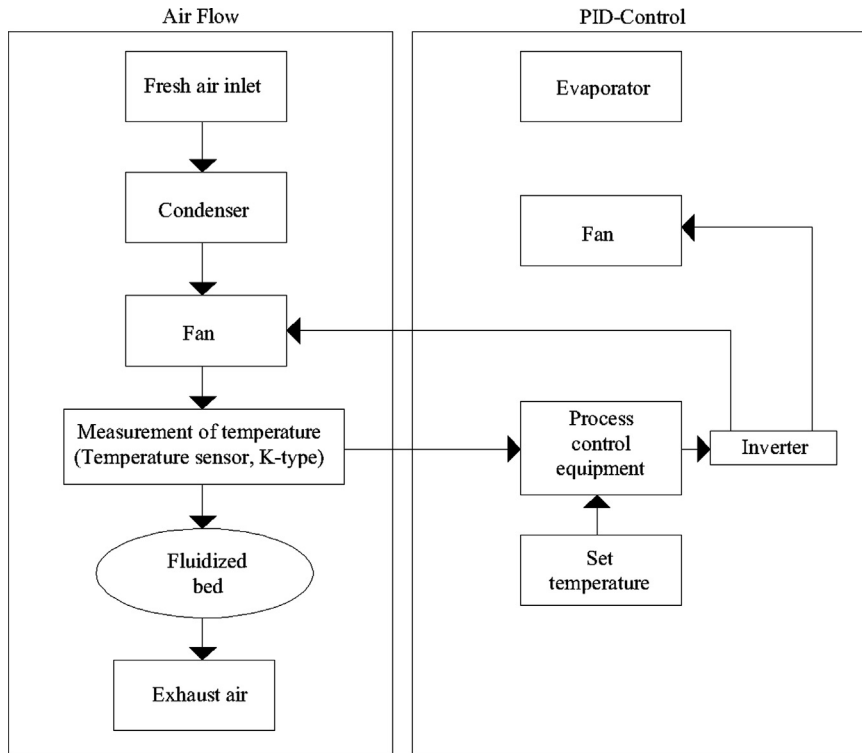


Fig. 2. Flow diagram of temperature control.

5. Evaluation of the heat pump dryer performance

The whole system COP_{ws} can be defined with the energy required for the compressor and fans can be represented as

$$COP_{ws} = \frac{\dot{Q}_{cd}}{\dot{W}_{c2} + \dot{W}_{f7} + \dot{W}_{f8}} \quad (12)$$

The SMER can be defined as the energy required to remove 1 kg of water and may be related to the power input to the compressor ($SMER_{hp}$) or to the total power to the dryer including the fan power and the efficiencies of the electrical devices ($SMER_{ws}$), as given by Jia et al. [8].

$$SMER_{ws} = \frac{\dot{m}_d}{\dot{W}_{c2} + \dot{W}_{f7} + \dot{W}_{f8}} \quad (13)$$

During the drying process, the energy utilization ratios (EURs) of fluidized bed dryer were calculated as in the following Eq. [3].

$$EUR_{fbd} = \frac{\dot{Q}_{fbd}}{\dot{Q}_{cd}} \quad (14)$$

$$EUR_{fbd} = \frac{\dot{m}_{ia}(h_{ia} - h_{oa})}{\dot{m}_{ia} \cdot C_{p,air} \cdot (T_{ia} - T_{fdi})} \quad (15)$$

6. Exergy analysis

Exergy is very important for the evaluation of drying equipment. For this reason, exergy inlet, exergy outlet, exergy loss and exergy efficiency of the drying process can be calculated by the following Equations [9,10]. Exergy inlet to the fluidized bed dryer:

$$e_{ia} = [h_{ia} - h_o - T_o(S_{ia} - S_o)] \quad (16)$$

in the equation;

$$h_{ia} - h_o = \bar{C}_p(T_{ia} - T_o) \quad (17)$$

$$S_{ia} - S_o = \bar{C}_p \ln\left(\frac{T_{ia}}{T_o}\right) \quad (18)$$

It is clarified as shown above.

If Eq. (15) is re-organised in accordance with Eqs. (17) and (18):

$$e_{ia} = \bar{C}_p \left[(T_{ia} - T_o) - T_o \ln\left(\frac{T_{ia}}{T_o}\right) \right] \quad (19)$$

Eq. (19) is achieved, where \bar{C}_p defines the average specific heat of drying air, can also be written as follows:

$$\bar{C}_p = C_{pa} + \omega_{ia} \cdot C_{pv} \quad (20)$$

By applying Eqs. (19–23), the inflow and outflow of exergy can be found depending on the inlet and outlet temperatures of the drying chamber. Hence, the exergy loss is determined by:

$$\sum E_{xl} = \sum E_{xi} - \sum E_{xo} \quad (21)$$

The equation of exergy outflow can also be written as follows:

$$e_{oa} = [h_{oa} - h_o - T_o(S_{oa} - S_o)] \quad (22)$$

If the similar expressions that are used to describe Eq. (17) are also used for Eq. (23)

$$e_{oa} = (C_{ps} + \omega_{ia} \cdot C_{pv}) \left[(T_{oa} - T_o) - T_o \ln\left(\frac{T_{oa}}{T_o}\right) \right] \quad (23)$$

Eq. (23) is achieved.

The quantity of the exergy loss is calculated by applying Eqs. (15–22). The exergetic efficiency can be defined as the ratio of the product exergy to exergy inflow for the dryer chamber. However, it is explained as the ratio of exergy outflow to exergy inflow for the chamber. Thus, the general form of exergetic efficiency is written as

$$\eta_{ex} = \frac{e_{oa}}{e_{ia}} \quad (24)$$

7. Uncertainty analysis

An uncertainty analysis was performed to assign credible limits to the accuracy of the reported values. Measured data uncertainty was calculated by using following Eq. [11]. Calculated uncertainty value is shown in Fig. 3.

$$x_m = \frac{1}{N} \sum x_i \quad (25)$$

$$V = \frac{1}{(N-1)} \sum (x_i^2 - x_m^2) \quad (26)$$

$$S = \sqrt{V} \quad (27)$$

$$a = \frac{1}{\sqrt{N}} \quad (28)$$

$$U = \sqrt{\sum_{i=1}^R a_i^2 \cdot S_i^2} \quad (29)$$

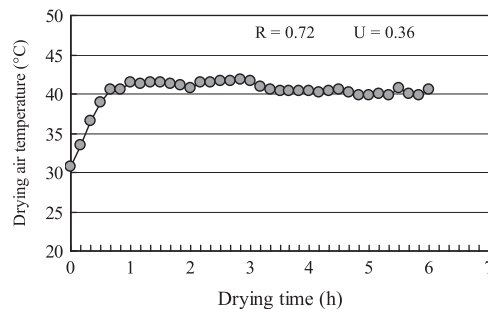


Fig. 3. Drying air temperature versus drying time.

8. Result and discussion

The variation of drying air temperature in terms of the drying time is shown in Fig. 3. The set temperature and measured temperature from process control equipment were compared through a regression analysis. Regression analysis was found as 0.72 and the measured temperature uncertainty was calculated as ± 0.36 °C.

The variation of moisture content and moisture ratio versus the drying time were calculated from the eqs. (1–4) and given in Figs. 4,5. Parsley and mint have similar moisture content and moisture ratio as in Fig.4 and Fig.5 whereas basil is dried more slowly than parsley and mint as seen Fig. 4 and Fig. 5.

Heat delivered in the condenser was changed according to air velocity in the fluidized bed dryer. As the air velocity increased, the heat delivered in the condenser increased and vice versa. This variation is shown Fig. 6.

Energy utilization ratio in the fluidized bed dryer was changed depending on the moisture content in the crops. Both energy utilization ratio and moisture ratio were decreased during the drying period. The variation of energy utilization ratio versus the drying time is shown Fig. 7.

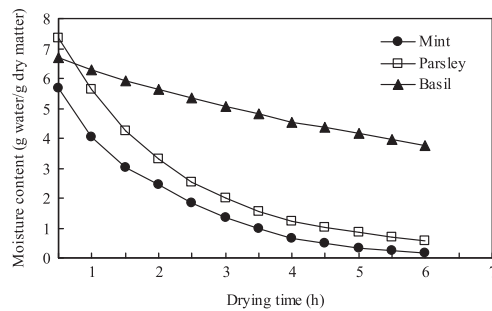


Fig. 4. Variation of moisture content with drying time.

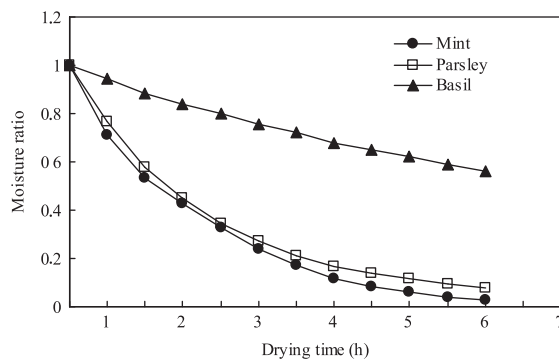


Fig. 5. Variation of moisture ratio with drying time.

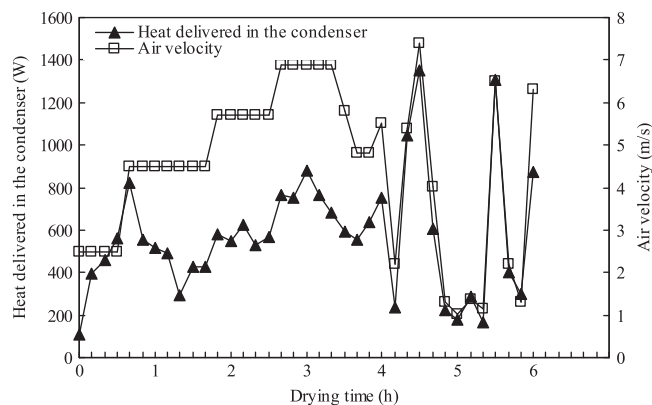


Fig. 6. Variation of heat delivered from the condenser and air velocity in the dryer.

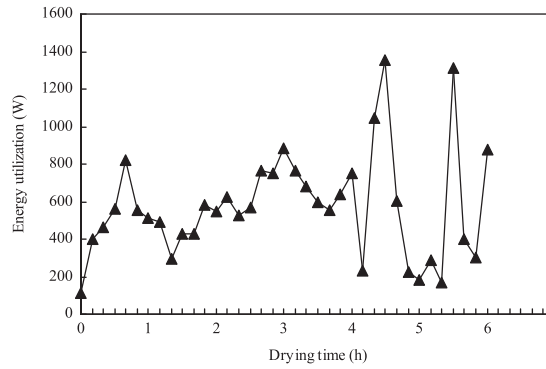


Fig. 7. Variation of energy utilization ratio versus the drying time.

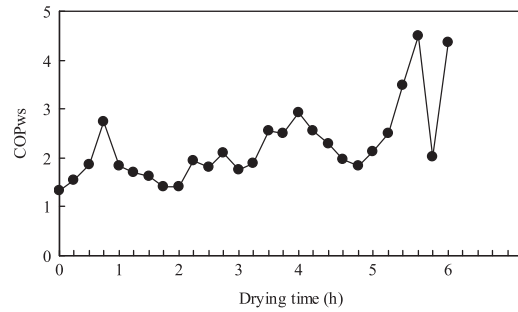


Fig. 8. Variation of COP_{ws} versus the drying time.

Table 2

Evaluation of heat pump dryer performance.

Dried product	COP_{ws}	$SMER_{ws}$ (g/Wh)	Drying time (h)	Initial and final moisture content (g water/g dry matter)	Drying air temperature ($^{\circ}C$)
Mint	1.91	0.00916	6	5.67–0.167	40
Parsley	1.91	0.00899	6	7.33–0.587	40
Basil	1.91	0.00421	6	6.69–3.77	40

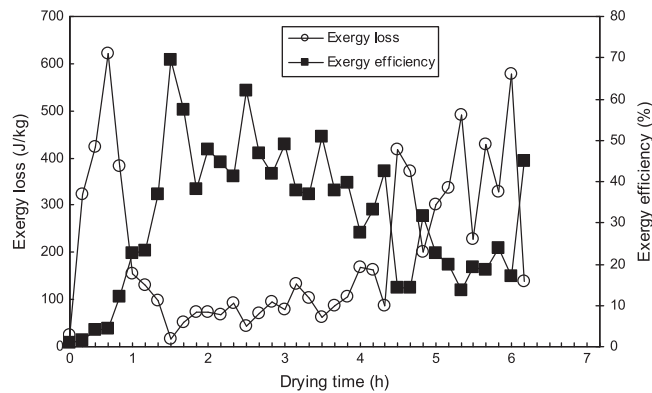


Fig. 9. Variation of exergy loss and exergy efficiency versus the drying time.

The coefficient of the heating performance of the whole system (COP_{ws}) was calculated from Eq. 12. COP_{ws} was periodically changed by the drying air velocity. This variation can be seen in Fig. 8. Average COP_{ws} was calculated during the drying period and given in Table 2. The whole performance of an HPD might be determined by the specific moisture extraction rate (SMER). The SMER was calculated from Eq. 13 and shown in Table 2.

Exergy directly dependent on temperature changed in the dryer. As the moisture content decreased, the exhaust air temperature increased and similarly exergy efficiency increased. While the exergy loss increased, the exergy efficiency decreased as shown in Fig. 9.

9. Conclusion

In this research, PID controlled heat pump system was connected with the fluidized bed chamber. As a result, the PID controlled heat pump fluidized bed dryer was manufactured after an experimental analysis of drying with mint, parley and basil. Experimental results discussed are as follows:

- In the current study, velocity of evaporator fan was adjusted instead of recirculation air using.
- Three different crops were dried in fluidization at the same time.
- Heating coefficient of performance of the whole heat pump system was obtained as 1.91.
- Drying temperature was controlled with a sensitivity of 0.36 °C.
- The best exergy efficiently was calculated as 70%.

References

- [1] Mujumdar AS. In: Handbook of industrial drying. New York: Crc Press; 1995.
- [2] Chua KJ, Chou SK, Ho JC, Hawlader MNA. Heat pump drying: recent developments and future trends. *Dry Technol: Int J* 2002;20(8):1579–610.
- [3] Ceylan I, Aktaş M. Energy analysis of hazelnut drying system-assisted heat pump. *Int J Energy Res* 2008;32:971–9.
- [4] Shi Q, Zheng Y, Zhao Y. Mathematical modeling on thin-layer heat pump drying of yacon (*Smallanthus sonchifolius*) slices. *Energy Convers Manag* 2013;71:208–16.
- [5] Fatouh M, Metwally MN, Helali AB, Shedid MH. Herbs drying using a heat pump dryer. *Energy Convers Manag* 2006;47:2629–43.
- [6] Şevik S, Aktaş M, Doğan H, Koçak S. Mushroom drying with solar assisted heat pump system. *Energy Convers Manag* 2013;72:171–8.
- [7] Aktaş M, Ceylan I, Yılmaz S. Determination of drying characteristics of apples in a heat pump and solar dryer. *Desalination* 2009;239:266–75.
- [8] Jia X, Jolly P, Clemets S. Heat pump assisted continues drying Part 2: simulation results. *Int J Energy Res* 1990;14:771–82.
- [9] Akbulut A, Durmus A. Energy and exergy analyses of thin layer drying of mulberry in a forced solar dryer. *Energy* 2010;35:1754–63.
- [10] Ceylan I, Aktaş M, Doğan H. Energy and exergy analysis of timber dryer assisted heat pump. *Appl Therm Eng* 2007;27:216–22.
- [11] Ceylan I, Kaya M, Gürel AE, Ergün A. Energy analysis of a new design of a photovoltaic cell-assisted solar dryer. *Dry Technol: Int J* 2013;31(9):1077–82.